

Innovation and Collaboration in Deep Mixing

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ABSTRACT: The deep mixing method of ground improvement blends additives to soil in-situ to increase strength, increase stiffness, and/or decrease hydraulic conductivity. The deep mixing method can be used to support embankments, structures, and excavations; mitigate liquefaction; and create seepage barriers. Contractors continually develop new equipment and procedures to improve the quality and decrease the cost of deep mixing. Equipment types include vertical-axis mixing rigs with one to six shafts, horizontal axis mixing machines with two rotating cutting wheels or one rotating drum, and chain-saw type mixing machines with a vertical post. Cutting and mixing teeth and blades vary in number, type, and orientation. The binder can be injected as dry powder or wet slurry, and air-slurry emulsions have been used. Slurry can be injected on the down-stroke or the up-stroke under low, moderate, or high pressure, and the injection nozzles can be located at the bottom of mixing shafts, along mixing blades, or from the shaft just above the mixing blades. Not all equipment and procedures are suitable for all soil conditions or project types, but more than one approach is feasible in most situations. Collaboration among owner, engineer, and contractor enable the benefits of innovations, and different contracting mechanisms enable different degrees of collaboration. Even in a design-bid-build contract, the engineer can develop the design and prepare the plans and specifications to allow for contractor innovation while protecting the owner's interests. Strategies include: expressing the geometric requirements in normalized terms, with appropriate limits; using statistically based acceptance criteria; making full use of construction quality control records; and involving the design engineer during construction.

INTRODUCTION

Opportunities for design and construction innovation in the deep mixing industry, as well as collaboration among designer, contractor, and owner, are facilitated by several factors: growing awareness and experience with deep mixing in many regions of the world; new applications of deep mixing to address a wide variety of infrastructure needs; increasing availability of reliable monitoring and process control equipment; and use of design-build and early-contractor-involvement procurement methods.

The state of practice in deep mixing is well represented by several recent publications, including those by Bruce (2012), Kitazume and Terashi (2013), and Bruce et al. (2013), as well as the GeotechTools.org website and proceedings of conferences in Okinawa (2009), New Orleans (2012), and San Francisco (2015) that featured deep mixing. The content of this paper is based largely on the information in these references, as well as the authors' recent project experiences.

For the purposes of this paper, the deep mixing method is defined as an in-situ ground treatment method in which soil is blended with binder and possibly other materials to improve strength, stiffness, and/or permeability characteristics, where the mixing is accomplished primarily using mechanical energy, although fluid energy may be used to enhance mixing. In the dry method of deep mixing, the binder is delivered in dry powder form, and in the wet method of deep mixing, the binder is delivered in binder-water slurry form.

Another categorization of mixing technologies is expressed by the terms "deep mixing" and "mass mixing." Although there are no precise boundaries between deep mixing and mass mixing, they tend to be differentiated by depth of treatment, percent area coverage, and strength. Deep mixing may extend to depths of 100 ft or more, and it is most often implemented in discrete elements, shear walls, or grid arrangements. Mass mixing produces 100% or nearly 100% treatment in plan view, and the depth of treatment is often 20 ft or less. Design strengths of ground improved by the deep mixing method are typically higher than design strengths of ground improved by the mass mixing method. The primary subject of this paper is deep mixing, but mass mixing and combined systems of deep mixing and mass mixing are also discussed.

This paper is organized in the following main sections: Deep Mixing Equipment and Processes, Deep Mixing System Configurations, Quality Control and Quality Assurance, and Plans and Specifications. The focus is on established factors and innovations that ultimately influence system performance and that should be considered collaboratively during design and construction to maximize benefits and reduce costs and risks.

DEEP MIXING EQUIPMENT AND PROCESSES

A comprehensive classification system for deep mixing equipment and processes is presented by Bruce (2012). For simplicity in the following discussion, deep mixing equipment is separated into four categories: vertical axis rotary equipment, horizontal axis cutting wheel equipment, chain-saw type mixing equipment, and horizontal axis rotating drum equipment.

Vertical Axis Rotary Equipment

Typical vertical axis rotary equipment includes single-axis and multiple-axis equipment with mixing blades located near the bottom of the shafts. Contractors and manufacturers have created equipment and process innovations to increase the thoroughness of mixing. For single-axis mixing using the wet method, tooling has been developed to provide stationary blades or counter-rotating blades, which

enhance mixing by increasing shear stresses in the mixture and inhibiting the tendency for a clump of unmixed soil to "go along for the ride" with the rotating blades. Multiple-axis mixing equipment includes cross-members that keep the parallel shafts in alignment, and these also serve the function of stationary blades for single-axis equipment. In addition, the rotating blades of multiple-axis equipment are typically arranged so they create overlapping columns comprising a single element, and the overlapping blades also tend to enhance mixing thoroughness. The inclination of mixing blades and the arrangement of cutting teeth on mixing blades also varies, and the blades and teeth are sometimes modified to suit the needs of a particular project. For single-axis vertical shaft rotary equipment using the dry method of deep mixing, the arrangement of paddles and blades can vary, and the rotation rates during binder injection are very high to distribute the binder throughout the column. Wet mixing and dry mixing are shown underway in Figures 1 and 2, respectively.

In addition to mechanical mixing energy, some deep mixing equipment and processes incorporate moderate to high pressure delivery of slurry through focused nozzles to help erode the soil and blend it with the slurry. The intent is not to enlarge column diameters with the pressurized slurry, but rather to enhance mixing. The nozzles can be located on the shaft and directed radially outward, or they can be located along one or more mixing blades and directed tangentially.



Figure 1. Deep mixing by the wet method using twin-shaft, vertical-axis equipment at earthen levee LPV 111 in New Orleans. Inset shows mixing blades in operation. (Photos courtesy of TREVIICOS).



Figure 2. Deep mixing by the dry method using single-shaft, vertical-axis equipment at Orleans Avenue Floodwall in New Orleans. (Photo courtesy of Hayward Baker Inc.)

With regard to vertical position, slurry delivery nozzles can be located near the top of the mixing blades or near the bottom of the mixing blades. When nozzles are located at the bottom of the mixing blades, the majority of the slurry is generally injected during penetration. If, instead, the slurry were to be injected during withdrawal, the slurry is not subject to mixing by the blades above the point of slurry injection. When nozzles are located near the top of the mixing blades, slurry can be injected during withdrawal and the trailing mixing blades blend the slurry with the soil.

When mixing equipment includes nozzles at the top and the bottom of the mixing blades and when the slurry delivery location can be selected during element construction, water can be introduced during penetration to help fluidize the soil to enhance mixing during withdrawal when slurry is delivery from the upper nozzles. However, to achieve treatment over the full depth of the element, slurry must be delivered to the bottom nozzles for at least a portion of the element depth near the bottom of the element. Clearly, this requires careful quality control during construction. If the same line is used for water delivery and slurry delivery, then slurry delivery at the ground surface must be engaged prior to the time that slurry is needed at the nozzles.

For all types of slurry delivery systems with vertical axis mixing, bottom treatment is an important aspect of construction. Generally, some type of re-stroking over the

bottom several feet of the element and/or dwell time at the bottom are used to provide sufficient slurry delivery and thorough mixing at the bottom of the element.

Modern data acquisition and control systems have been implemented for slurry preparation, slurry delivery, and mixing equipment. These include position by GPS, verticality, rotation rate, penetration and withdrawal rates, and slurry delivery rate. Some equipment can be pre-programmed to use different penetration rates over different depth intervals while holding the rotation rate and slurry delivery rate constant, thereby varying the binder delivery and the mixing energy to improve hard-to-treat zones (e.g., highly organic soils, peat, and plastic clay) differently from easy-to-treat soils like inorganic silty sand. Some equipment can also be programmed to vary the slurry delivery rate in proportion to the penetration rate so that the amount of slurry delivery per meter of depth can be held relatively constant, which capability can be used to avoid excess slurry delivery when dense materials slow the penetration rate.

The variations and innovations in equipment and processes described above create a great number of combinations that can produce desired outcomes, if each combination is appropriately implemented. For design-bid-build projects, these variations in equipment and process can be addressed by focusing plans and specifications on outcomes and normalized geometric requirements rather than overly restricting equipment, materials, and methods. For design-build and early-contractor-involvement-in-design projects, detailed project requirements can be tailored to the contractor's equipment and methods. These issues are discussed further in the section on plans and specifications.

One measure of mixing energy that has been widely used for vertical axis mixing machines is the blade rotation number, BRN, which is the number of blade passes per meter of element depth. For example, if a shaft has a pair of blades at each of four levels for a total of eight blades, the rotation rate is 20 rpm, the penetration rate is 0.4 m/min, the withdrawal rate is 2 m/min, and the slurry is injected during penetration from nozzles located at the bottom of the mixing blades, the BRN would be $8(20/0.4 + 20/2) = 480$ blade passes per meter.

BRN is best used as a quality control measure for a specific type of equipment because the same BRN does not imply the same degree of mixing energy for all technologies. For example:

- BRN does not distinguish among single-axis mixing without a stationary blade, single-axis mixing with a stationary blade, or multiple-axis mixing with overlapping columns and stationary spacer bars at the level of the mixing blades.
- BRN does not consider the vertical spacing between rotating blades.
- BRN does not consider the potential effects of blade and cutting tooth configuration.
- BRN does not consider the potential effects of moderate to high pressure slurry injection.

Despite these shortcomings, BRN remains a simple and very useful measure for quality control purposes on a specific project with specific equipment. Relatively low values of BRN may be sufficient for thorough mixing in sandy soils, while much higher values of BRN may be necessary for thorough mixing in stiff clay soils. The

amount of water introduced during slurry injection, as well as pre-mixing with water, will also influence the amount of mixing energy necessary to achieve thorough mixing.

It is important to note that BRN should only be calculated for blade passes that occur after the binder has been injected. Thus, if slurry is injected from nozzles at the top of the blades during withdrawal, only the blade passes during withdrawal should be included in the BRN calculation. Slurry injected from nozzles at the bottom of the mixing blades during withdrawal will receive very little mechanical mixing energy.

BRN is not well defined at the bottom of the element. As mentioned previously, re-stroking and/or dwell time is often done and is generally necessary to achieve thorough mixing at the bottom of elements, but the BRN calculation described above strictly applies only to the portion of the element above the bottom by a distance equal to the length of the shaft with blades.

In many applications, the amount of overlap between adjacent columns is important. Examples include when overlapping columns are used to create shear walls to resist lateral loads and when overlapping columns are used to create seepage barriers. Often, project plans and specifications require that the column overlap area be a certain percentage of the area of a single column or that the overlap distance of adjacent columns be a certain percentage of the column diameter. For shear walls, the objective is to achieve at least a minimum chord distance where adjacent columns overlap, and a simple analysis method for this requirement is provided in the FHWA Deep Mixing Design Manual (Bruce et al. 2013). When multiple-axis columns are used to create shear walls, the control of column overlap is much greater (and the uncertainty much less) within a multiple-column element than between one element and the next. Accordingly, designers should consider requiring smaller overlap ratios within elements than between elements, and the difference in overlap ratio can be based on tolerances for location and verticality of elements.

Another important consideration with respect to column overlap ratios is whether the deep mixed system design incorporates redundancy. When parallel shear walls oriented perpendicular to the slope alignment are used to provide stability, the deep mixed support system incorporates redundancy because, with good specifications by the designer and good quality control by the contractor, the likelihood of major misalignment between adjacent elements occurring at the same relative location along the side slope in several adjacent shear walls is very low. On the other hand, when deep mixed elements are used in a single line to create a seepage barrier, this is not a redundant system, and the effects of misalignment between adjacent elements could be significant, both in terms of seepage quantity and potential for piping erosion.

Further, the construction sequence can impact the degree of conservatism that should be employed in specifying the amount of overlap between adjacent elements. If a "primary-secondary" construction sequence is used, there would be less tendency for differences in ground conditions at the ends of elements to skew the element off alignment than if a "progressive" sequence is used.

Pulling these considerations together, the authors' general preferences, subject to project specific conditions and objectives, include the following:

- For critical seepage barriers constructed using deep mixed elements in a single line, a primary-secondary construction sequence with full column overlap

would provide a high degree of confidence that continuity is provided. This approach would eliminate single-axis mixing equipment, and it would make two-axis elements uncompetitive.

- For redundant shear walls installed to improve stability by resisting lateral loads, the minimum column overlap ratio within elements can be calculated using the approach in the FHWA manual (Bruce et al. 2013), and overlap distance ratios of 20% to 33% are common, depending on project requirements. The required overlap between elements would be larger than the required overlap between columns within elements, and for primary-secondary construction, this overlap distance ratio might range from 25% to 50% with a minimum of 2 ft. In our opinion, it would be unusual and generally unnecessary to require full column overlap for shear walls constructed using a primary-secondary approach. However, when progressive element construction is employed to construct deep shear walls in ground with cobbles and/or dense sand and gravel, a designer might judge that full-column overlap is necessary to provide confidence that elements will not drift due to differing conditions at the end of each element.

Horizontal Axis Rotary Cutter Wheels

Deep mixing equipment commonly known as Cutter Soil Mixing (CSM) employs two, horizontal-axis, rotary wheels with cutting teeth that overlap to create rectangular barrettes of soil-cement mixture, as shown in Figure 3. Penetration can be done with delivery of water or slurry, and slurry can be injected during withdrawal. If the formation being treated includes dry, stiff, or dense layers, using water during penetration can help prepare the ground for more thorough mixing when slurry is injected during withdrawal. The ports for fluid delivery are located at the center of the element, just above where the cutting wheels meet.

Inclinometers monitor the verticality of the mixing tool during penetration, and the cutting wheels can be used to "steer" the mixing tool, which provides means to control position of the element. Required overlap between adjacent elements depends on the application and the ground conditions. For repetitive shear walls constructed using a primary-secondary installation sequence, overlaps from 0.1 to 0.3 m have been applied. Overlaps equal to the rectangular barrette width are unnecessary for shear walls constructed using a primary-secondary installation sequence, in our opinion. Bottom treatment is typically done using re-stroking and/or dwell time at the bottom of the element. Difficult-to-treat layers, such as peat, have also been treated by re-stroking through those layers during withdrawal, which has at least three benefits: delivering additional slurry if needed, providing additional mixing energy, and blending in material from above and below the difficult layer.

For CSM, there is not a clear equivalent to BRN. Nevertheless, penetration/withdrawal rates and mixing wheel rotation rates are recorded continuously, and these can be used to monitor consistency of construction operations from element to element on a project. Similarly, water and slurry injection rates are recorded continuously.



Figure 3. Cutter soil mixing equipment. (Photo courtesy of Pacific Ground Engineering)

Chain-Saw Type Mixing Equipment

At least two types of equipment in North America use continuous belts of links with attached teeth that rotate around a post inserted into the ground from a track-mounted mixing machine that slowly travels along the alignment of a continuous wall.

For one of these types of chain-saw mixing equipment, the post is always inserted vertically with help of a crane. This equipment uses water-binder slurry that is prepared in a separate stationary mixing plant and pumped in supply lines to the mixing equipment. For this equipment, the speed of the chain, the speed of the mixing rig, and the slurry delivery rate are all continuously monitored and documented.

For the other type of chain-saw mixing equipment, which is shown in Figure 4, the post is typically swung into the ground from a near horizontal position to a vertical position, and this can be done without a crane. However, if necessary, a vertical starter trench can be excavated under slurry, and the post can be lowered into the starter trench with a crane. This equipment generally uses dry binder delivered from a hopper at the surface and water delivered at a port located part way down the blade. Binder-water slurry has been used with this equipment, but separate injection of dry binder and water is more common. The dry binder delivery rate is controlled by an auger feed system, the water delivery is controlled with a manually operated valve, and the chain speed and equipment travel speed are manually controlled by the rig operator. Until recently, continuous electronic monitoring and control of the process parameters had not been implemented. Nevertheless, this type of equipment has been

used successfully to produce well mixed soil-cement that satisfied project requirements for continuity, mixing thoroughness, strength, and hydraulic conductivity on a number of projects. Recently, continuous monitoring of process control parameters has been developed and implemented.



Figure 4. Chain-saw type mixing equipment in operation, with post and chain in the ground, binder hoppers above the post and chain, wet-mixed spoils behind the mixing rig, and inset showing toothed chain.

Chain-saw type mixing equipment is different from vertical axis rotary mixing and CSM in several important ways, including:

- Chain-saw mixing is a continuous process as long as the equipment can be operated without stopping long enough for the mixture to set up. Accordingly, there is not a need to carefully control overlap between short elements. When the equipment must stop within a long run for maintenance or construction logistics reasons, the equipment is advanced a distance using water alone or water and bentonite. At re-start, the equipment cuts back into previously hardened material and then advances to create a continuous wall.
- The continuous rotation of the chain from top to bottom of the element and back blends materials throughout the depth of the wall so that easy-to-treat and difficult-to-treat layers are blended to a high degree. Vertical axis rotary mixing and CSM also do this to some extent, and this can be enhanced by re-stroking, but the resulting vertical blending is not as thorough as with chain-saw type mixing equipment.

- Focused bottom treatments, like local re-stroking and dwell time, are not necessary with chain-saw type mixing equipment.
- Chain-saw mixing equipment is not as maneuverable or adaptable to specialized geometries as are vertical axis rotary mixing equipment and CSM equipment, and this applies both in plan view and with regard to depth of treatment. Chain-saw mixing equipment is most efficient for long runs, such as cutoff walls.

Horizontal Axis Rotary Drum Mixing

Mass mixing can be done using a toothed drum attached to a backhoe, as shown in Figure 5. Treatment depths typically do not exceed about 20 ft. The binder can be delivered in either dry powder form or in slurry form. Current practice involves staking adjacent cells for treatment, controlling and monitoring the amount of binder delivered to each cell, and controlling and monitoring the amount of time the mixing tool is in each cell. Thoroughness of mixing depends upon the mixing rig operator, who must move the mixing drum through all parts of the cell being treated to distribute and blend the binder with the in-situ soil.



Figure 5. Horizontal axis rotary drum mixing underway using the wet method, and inset showing mixing drum. (Main photo courtesy of Hayward Baker Inc.)

Horizontal-axis rotary drum mixing is not done to great depths, and it cannot penetrate hard materials. However, this technology can be very useful for economically stabilizing large areas to shallow depths. Because the entire area subject to load is treated, strength requirements are typically not as high as for applications using isolated elements, shear walls, or grids.

DEEP MIXING SYSTEM CONFIGURATIONS

Deep mixing can be installed as isolated elements, shear walls, cutoff walls, cells, and complete area treatment.

Isolated elements are installed by a single set-up of the mixing equipment, and they do not touch other elements. An element may consist of a single-axis vertical rotary column, a multiple-axis vertical rotary element comprising two or more overlapping columns, or a rectangular CSM element. The term "element" is not applicable to soil-cement produced by chain-saw mixing equipment or horizontal axis rotary drum equipment. Isolated elements can be used to support buildings on mat foundations, tanks with suitable load transfer platforms, and the central portions of embankments. Isolated columns are generally not efficient in resisting lateral loads, whether from sloping ground, earthquake shaking, or other sources. Vertical axis mixing equipment and CSM equipment are used to install isolated elements.

Shear walls are effective for resisting lateral loads in the direction of the shear wall orientation. Consequently, shear walls have been used under the side slopes of embankments and at the toes of dams, with the shear walls oriented perpendicular to the alignment of the embankment or dam. Vertical axis mixing equipment and CSM equipment are effective for installing continuous shear walls, with proper attention to overlap between elements. In principle, chain-saw type mixing equipment could be used for shear walls, but the set-up logistics for each shear wall would be challenging.

The deep mixing method has been used many times to construct cutoff walls that serve as seepage barriers for levees, dams, excavations, and other purposes. Multiple-axis vertical rotary equipment, CSM equipment, and chain-saw type mixing equipment are all effective for constructing cutoff walls. Careful attention to element overlaps is warranted when using vertical axis mixing equipment and CSM equipment to construct seepage barriers.

Rectangular grid arrangements of soil-cement walls can resist lateral loading in all horizontal directions and can reduce the potential for liquefaction of loose soils contained within the cells. For a project in which weak ground was treated by deep mixing beneath a high, mechanically stabilized earth wall that was shaped like an "L" in plan view, soil-cement shear walls were used for each leg of the "L", and a grid arrangement was used at the corner of the "L" to resist lateral loads in both directions.

Mass mixing has been used for a variety of purposes, including environmental stabilization, but the main focus here is on structural support. Mass mixing can create working platforms for equipment and to create load transfer platforms that support overlying structures or embankments and transfer these loads to deeper elements that extend through weak or compressible layers to more competent bearing layers at depth. Mass mixing has also been used on its own to support embankments when the depth to a suitable supporting stratum is relatively shallow.

Mass mixing is most commonly done using large-diameter single-axis vertical rotary equipment and horizontal axis rotary drum equipment. However, mass mixing has been done using multi-axis vertical rotary mixing and CSM equipment. The authors' are also aware of a project in which chain-saw type equipment is being

considered to create a 100% stabilized block of soil-cement to form a low-height gravity dam section several miles long.

A useful combination of mixing configurations involves mass mixing to create a load transfer platform and isolated deep-mixed elements to carry the load to a suitable bearing layer at depth. This has been done in a variety of ways. A project was successfully completed by first using horizontal axis rotary drum equipment to create a load transfer platform about 10 ft thick, which also served as a construction working platform. Holes were then drilled through the load transfer platform, and single-axis vertical rotary columns were then installed through the holes to about depth 60 ft. Tests were performed to demonstrate suitable bond capacity between the deep mixed columns and the mass mixed zone. On another project, twin-axis vertical rotary elements were used to create both the shallow load transfer platform and the isolated deep mixed elements that carried the load from the transfer platform to a bearing layer at depth. In this instance, it was not necessary to drill holes through the load transfer platform; instead, when the mixing equipment arrived at the location of a deep element, mixing simply continued down through the weak layers to the necessary depth to provide adequate bearing.

QUALITY CONTROL AND QUALITY ASSURANCE

In practice, the terms quality control (QC) and quality assurance (QA) are sometimes used almost interchangeably. Although QC and QA activities overlap, the emphasis here is that QC represents the set of activities that the contractor takes to control and document the quality of the work. To use vertical axis mixing as an illustrative example, QC includes: controlling and documenting all aspects of element location and geometry, binder material type and quality, slurry component quantities, slurry mixing and handling procedures, mixing equipment details, slurry delivery rate, penetration rate, withdrawal rate, rotation rates, specialized bottom treatment, and surface protection. On the other hand, QA represents the set of activities performed by the contractor, the owner, and the owner's engineer to verify that the work has been done in accordance with the requirements of the plans and specifications. In this context, QA includes: careful review of the QC documentation; independent observations and measurements of construction geometry and processes; and sampling, observations, and testing of the mixed material.

An important QC/QA concept for deep mixing is a trial/demonstration program that takes place as part of the deep mixing construction contract and before production mixing begins. Purposes of the trial/demonstration program include: allowing the contractor to try different mix proportions, mixing parameters, and tooling details; demonstrating which combination of factors can reliably achieve the specified outcomes; and exercising and familiarizing all parties with the QC/QA procedures. It is not necessary that all of the test/demonstration elements achieve the specification requirements. In fact, one of the purposes of the trials is to allow the contractor to determine what materials and process details will economically and reliably achieve the specified requirements. In addition to recording and documenting all QC activities, the trial/demonstration elements are normally subjected to a much higher frequency of sampling and testing, which are considered here as primarily QA

functions, than the production elements. After appropriate materials and processes are established in the trial/demonstration program, these same parameters are used in production mixing with a much reduced frequency of sampling and testing. The concept is that confidence that the production elements will satisfy the specification requirements is provided primarily by QC activities and documentation demonstrating that production elements are installed using materials and processes that were successful in the trial/demonstration program. However, spot checking the results with QA sampling and testing is still necessary, and project-specific QC/QA plans should be developed with consideration of the potential that subsurface conditions for production elements could be different from conditions for test/validation elements. For stabilization of earthen levee LPV 111 in New Orleans, five trial/demonstration programs were conducted at different locations along the 5-mile length of the project.

There continues to be much discussion about the roles that wet-grab sampling and coring should play in QA for demonstrating satisfaction of specification requirements. For deep mixing support applications, the authors favor placing primary reliance on coring, although there are exceptions as discussed below. Coring is favored because:

- The soil cement mixture is allowed to cure under in-situ conditions of pressure and temperature, and without additional mixing imparted by wet-grab sampling, wet sample screening, and wet sample preparation in cylindrical curing molds.
- Coring reveals the mixture condition from top to bottom of the element, rather than at the few depths of discrete wet-grab sampling.

Coring has been criticized because it can be more expensive than wet-grab sampling, and because the coring process may damage the core specimens. Coring does cost more than wet grab sampling, but the authors believe the benefits outweigh the costs. The authors have also seen coring successfully completed in a wide range of materials, including in mixtures with gravel particles in a relatively weak matrix of soil-cement, as shown in Figure 6. Some of the best coring procedures employ triple-tube wire-line coring with side-discharge bits. The skill of the coring rig operator is very important, and variations in rotation rate, penetration rate, and drilling fluid pressure can influence the coring outcome. Ordinarily, the contract documents require the contractor to perform the coring at locations selected by the engineer, and the coring must satisfy requirements to recover certain percentages of the core run length for each core run. The engineer selects coring locations based on the QC documentation, as well as the engineer's observations of construction and knowledge of subsurface conditions. If the owner/engineer believes that high quality coring equipment and procedures are being used, and that adequate core recovery is not possible due to the hardness and distribution of coarse particles in a relatively weak soil-cement matrix, the owner/engineer may allow a combination of wet-grab sampling and testing, combined with down-hole optical televiewer logs of cored holes as an alternative to achieving the specified core recovery and strength of cored specimens. In this alternate approach, the strength of specimens from wet-grab samples provides an indication of suitable mixture components, e.g., binder, water, and soil, and the optical televiewer images can permit an assessment of the thoroughness of mixing over the full depth of the element.



Figure 6. Good core recovery of soil-cement mixture with coarse sand and gravel in a weak matrix, with inset showing side discharge core bit.

Even though strength tests from wet grab samples are not recommended here for routine use to demonstrate satisfaction of specification requirements for deep mixing support applications, tests on specimens formed from wet grab samples can serve an important function for the contractor, which is to give an early indication of mixture strength and strength gain with time. Ordinarily, there are no prohibitions against the contractor obtaining wet grab samples, although specifications typically require that all wet-grab sample attempts and test results be reported to the owner or the engineer. If the contractor uses the mixing equipment itself to obtain the wet-grab samples, the owner/engineer would typically select elements to be cored that had not been subjected to wet-grab sampling to avoid the effects of additional mixing energy imparted during the wet-grab sampling process. However, cores in elements subjected to wet-grab sampling can be done to compare wet grab samples and core samples and to investigate elements that wet-grab sampling and testing indicate may be weak.

For mass mixing applications, using 100% or nearly 100% area treatment generally requires lower strengths and reduces concerns about isolated zones of untreated or poorly treated material. In such circumstances, design can be done by assuming a relatively large coefficient of variation on strength, which reduces the variability factor applied to the specified soil-cement strength to produce a design strength as described in the FHWA Design Manual (Bruce et al. 2013), and wet grab sampling can be used in lieu of coring, provided that other QC/QA activities are well done, including continuous observation of construction activities by a representative of the owner/engineer.

For cutoff wall applications, permeability tests on core samples are not normally used to demonstrate satisfaction of permeability requirements because of the potential

for coring-induced damage to cause large increases in hydraulic conductivity of specimens. Alternatively, permeability tests can be performed on wet grab samples, or using single-well (slug) tests in cored holes. If single-well tests are used, important considerations include:

- The seepage conditions for a single-well test in a cored hole are three dimensional. Consequently, data reduction should be done using a cutoff-wall method (e.g., Teeter and Clemence 1986, Britton et al. 2002, Choi and Daniel 2006) rather than a method for an aquifer of great lateral extent (e.g., Hvorslev 1951).
- The coring process can damage the cutoff wall. If a single-well test fails to satisfy the specification acceptance criterion and if an optical televiewer log demonstrates vertical cracks in the wall of the cored hole that are not reflected in recovered core, the failed test should not be counted against satisfaction of the acceptance criteria. Instead, a replacement test should be permitted in a new cored hole.

PLANS AND SPECIFICATIONS

The foregoing discussion illustrates that: (1) a wide range of mixing approaches are possible, and (2) detailed QC/QA procedures are necessary to provide assurance that the outcomes satisfy requirements. For most projects, several different combinations of equipment, materials, and processes can achieve the desired outcomes. To encourage innovation and fair competition in design-bid-build procurement, plans and specifications should avoid, to the extent possible, specifying means and methods and should instead focus on outcomes related as closely as possible to the design intent.

Regarding geometry, consider an embankment support application with isolated elements under the central portion and shear walls oriented perpendicular to the embankment centerline under the side slopes. Specifications of the geometry for this situation could include:

- Specification of the area replacement ratio under the central portion, along with a maximum clear distance between adjacent columns. This would allow for different element sizes to be competitive, provided that the clear spacing between columns does not become too large for low embankments, which otherwise could experience differential surface settlements.
- Specification of the area replacement ratio for the shear walls under the side slopes, with a maximum clear distance between adjacent shear walls. The reasoning is similar to that for the central portion of the embankment, except that maximum spacing in this case may be based on considerations of extrusion between shear walls as well as differential surface settlement.
- For the shear walls, normalized overlap requirements between elements may be larger than normalized column overlaps within elements because the latter are more completely controlled.

Regarding mix designs, this is normally left up to the contractor, including: binder materials (e.g., use of Portland cement or a mixture of Portland cement and ground granulated blast furnace slag), water-to-binder ratio of the slurry, and volume ratio (volume of slurry to volume of soil to be mixed). The owner/engineer may have

performed some laboratory bench-scale tests during the design phase that can be useful to the contractor, and the contractor may perform additional laboratory bench-scale tests, but field mixing and curing are different from laboratory mixing and curing, and different field mixing equipment and process procedures can produce different outcomes for the same mixture proportions. It is up to the contractor to propose materials, equipment, and processes to produce the specified outcomes. The contractor's proposals should be subject to owner/engineer approval, but the contract documents should also make clear that such approval does not release the contractor from obligation to satisfy the specification requirements.

The strength of deep mixed material is variable, and this variability should be taken into account during design. Procedures for this are described in the FHWA manual (Bruce et al. 2013). The fact of variability should also be reflected in the project specifications by using a statistically based specification. The FHWA manual recommends that design calculations and acceptance criteria be based on 80% of specimens from each cored hole and 90% of specimens from the entire project or project phase should equal or exceed the specified strength. In this approach, there is no need to specify a minimum strength. Restrictions are also placed against low strengths at the same depth range in nearby cores to guard against a weak layer of treated soil. If a core specimen fails due to a clod of unmixed soil that is not proportionately representative of unmixed zones in the full size column, then the owner/engineer may allow a test result from another specimen within the same core run to be substituted for the failed test result. The idea here is that a 2-inch clod of unmixed soil in a 3-inch diameter core sample would correspond to a boulder-size piece of unmixed soil in a full size column, and if there is no indication of such large pieces of unmixed soil in the columns based on core recovery or observation of spoils, then a test on a specimen containing a 2-inch clod of unmixed soil would not be representative of the entire column.

Specifications should carefully define the terminology to be used on the project, such as defining columns, elements, panels, walls, etc. In addition, the term "cement factor" or "binder factor" that quantifies the amount of binder in the mixture should be carefully defined. In the authors' experience, most contractors prefer defining binder factor as the weight of dry binder per unit volume of soil to be mixed, but some contractors prefer to define binder factor as the weight of dry binder per unit volume of the mixture. If the nominal value of binder factor is 200 kg/m^3 , for example, there will be less binder in the mixture using the first definition than when using the second definition. Project communication can be clear using either meaning, but the selected meaning should be clearly defined, and it should be used consistently by all parties.

Contractors often object to use of the word "homogeneous" in specifications to describe the soil-cement produced by deep mixing, and they have a valid point. To those not familiar with deep mixing, this word can imply a degree of uniformity that is not practically achievable, nor necessary. In lieu of using words like "homogeneous", it is much better to provide precise descriptions of what is expected. An example of a more precise specification requirement than use of the term "homogeneous" would be that recovery of treated soil, which is the total core recovery minus the sum of the lengths of recovered core that do not have any hardened soil-cement in the core cross section, should be at least 80% for every core run.

Alternatives to design-bid-build contracts include design-build and early-contractor-involvement-in-design. In these alternate contracting approaches, the deep mixing support system can be tailored to the contractor's equipment, and specific element dimensions and locations can be called out on the plans. This simplifies the design work for the engineer and the submittal work for the contractor, and it permits optimizing geometry during the design phase. However, the project specifications should still provide the same detailed QC and QA requirements as for a design-bid-build project in order to provide the owner with assurance that the intended outcomes are achieved.

For all contracting approaches, it is critically important that the design engineer be involved during construction rather than completely turning over QA activities to personnel who are not familiar with the project design basis. The latter approach can result in undesirable "blind" enforcement of contract provisions.

SUMMARY STATEMENT

The principle idea the authors wish to convey is that deep mixing technology continues to evolve and owners/engineers should prepare plans and specifications that allow for innovation and fair competition while still protecting the owner's interests. This is a worthwhile goal for most types of construction, and it is especially important for deep mixing due to continuing technology improvements, variations in subsurface conditions from site to site, and differing performance objectives for different types of facilities. To achieve this goal, specifications of outcomes is preferred over specification of equipment, materials, and processes. Furthermore, the importance of a thorough field test/demonstration program prior to production mixing is emphasized.

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